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An Approach for Describing Electrical Characteristics of Precipitated Dust Layers

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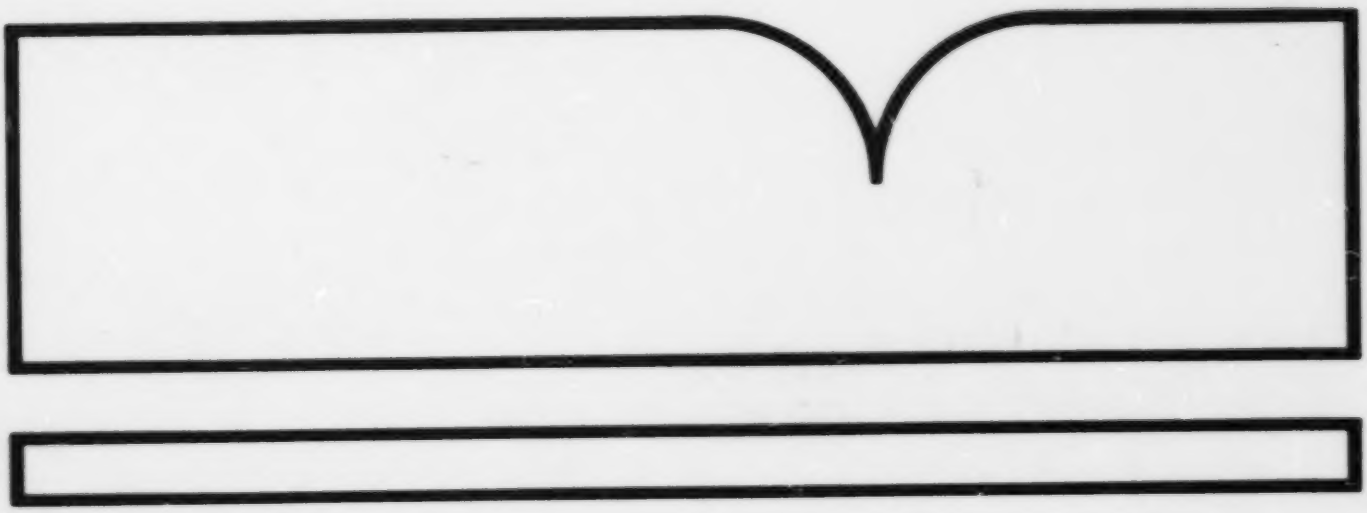

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16. ABSTRACT: The paper proposes an approach for describing the electrical characteristics of electrostatically precipitated dust layers. It describes the macroscopic electrical properties of the dust layer, by coupling the current transport equation and Poisson's Equation. It attributes the electrical breakdown of the dust layer to enhanced values of the local electric field due to the combined effects of polarization in the dielectric layer and the contribution to the electric field from the space charge distribution in the layer. Models based on this approach appear to offer the potential for describing the observed electrical behavior. It also discusses the experimental data which are needed for developing this approach.

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An Approach for Describing Electrical Characteristics of Precipitated Dust Layers

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An approach for describing the electrical characteristics of electrostatically precipitated dust layers is proposed. The macroscopic electrical properties of the dust layer are described by coupling the current transport equation and Poisson's Equation. The electrical breakdown of the dust layer is attributed to enhanced values of the local electric field due to the combined effects of polarization in the dielectric layer and the contribution to the electric field from the space charge distribution in the layer. Models based on this type of approach appear to offer the potential for describing the observed electrical behavior. The experimental data which are needed for developing this type of approach are discussed.

Once a dust layer is deposited on the collection electrodes of an electrostatic precipitator, the negative corona current must pass through the particulate layer to the grounded collection electrode. The voltage drop (V_L) across the particulate layer is

$$V_L = j\rho L \tag{1}$$

where

j = current density through the layer (A/cm^2),
ρ = average resistivity of the layer (ohm-cm), and
L = thickness of the layer (cm).

The average electric field in the particulate layer (E_{ave}) is given by

$$E_{ave} = j\rho \tag{2}$$

The value of E_{ave} can be increased to the point that the layer breaks down electrically. When this breakdown occurs, one of two possible situations will ensue. If the average electrical resistivity of the particulate layer is moderate ($\sim 0.1 - 1.0 \times 10^{11}$ ohm-cm), the applied voltage may be sufficiently high so that a spark will propagate across the interelectrode space. The rate of sparking will determine the operating electrical conditions in such a circumstance. If the average electrical resistivity of the particulate layer is high ($>10^{11}$ ohm-cm), the applied voltage may not be high enough to cause a spark to propagate across the interelectrode space. In this case, small holes or craters are formed in the particulate layer from which back corona discharges occur and are the source of positive ions which flow through the gas toward the corona electrode. This condition is called back corona or back discharge. The effect of these positive ions is to reduce the amount of negative charge on the particles in the gas stream due to bipolar charging which in turn reduces the space charge component of the electric field and also produces positively charged dust particles. Both the magnitude of particle charge and the rate of particle charging are affected adversely by back corona. Useful precipitator current is therefore limited to values which occur prior to electrical breakdown whether the breakdown results in sparkover or back corona.

Although several experimental studies[1-10] have been performed to investigate the electrical breakdown of the particulate layer, only limited theoretical studies[8,9,11-13] have been performed to model the electrical phenomena which occur in the layer. At the present, no comprehensive theoretical model is available to describe the electrical conditions in the collected particulate layer. This type of model is needed in order to develop a complete model for electrostatic precipitation and in order to provide a fuller understanding of the physical mechanisms which produce the observed electrical phenomena.

In this paper, a theoretical approach for describing the electrical characteristics of precipitated dust layers is proposed and discussed. The macroscopic electrical properties of the dust layer are described by coupling the current transport equation and Poisson's Equation. Charge transport in the layer is assumed to occur by the migration of alkali metal ions such as those of sodium and lithium. This situation exists for high temperature (greater than 200°C) volume conduction in many fly ashes.[14] Although the model discussed here can be readily extended to the case of surface conduction, for the sake of clarity only volume conduction will be considered.

The electrical breakdown of the dust layer is attributed to enhanced values of the local electric field due to the combined effects of polarization in the dielectric layer and the contribution to the electric field from the space charge distribution in the layer. These two descriptions are mutually compatible because the layer consists of nearly spherical particles which

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behave much like a dielectric, but are capable of conducting small ionic currents when subjected to strong electric fields. In fact, fly ash layers have been characterized in the literature[11,15] as being analogous to a leaky capacitor.

It is appropriate to discuss polarization charge induced on the surfaces of the particles because the porous layer contains flue gas trapped between the particles. Hence, the layer consists of two dielectric materials which are mixed in a manner that resembles a nonhomogeneous dielectric. When an electric field is applied to the layer, polarization charges are induced on the boundaries between the two dielectrics. Since the area of contact between two adjacent spheres constitutes only a small fraction of the total area of the spheres, most of the induced surface charge is not neutralized by the opposite charge on the adjacent sphere. These induced charges are not free to migrate on the surface of the spheres. Because the spheres in contact provide continuous paths for the migration of free ions through the layer, it is consistent to discuss the transport of small currents through the layer of polarized particles.

The density of space charge associated with the mobile ions may be relatively small in comparison with the density of polarization charge. However, the polarization charge is distributed in a manner that makes no contribution to the macroscopic electric field, while the space charge associated with the mobile ions does contribute to the macroscopic field. Even though the polarization charge does not contribute to the macroscopic field, it can contribute substantially to the local field in the gas pockets between particles. In the present model, it is the total local field in the region between particles which is effective in breaking down the gas trapped there. Breakdown of the gas in one of the cavities between particles may ultimately lead to the development of a crater which penetrates the entire layer.

The resistivity mentioned previously is a macroscopic parameter. Its microscopic analog is related reciprocally to the product of the charge carrier density and the carrier mobility. For volume conduction the resistivity decreases with increasing temperature both because the ions are more mobile with increased thermal energy and because the number of free mobile ions increases with thermal energy.

Models formulated from the proposed approach offer the potential of providing the following information:

(1) Voltage-current characteristics of the particulate layer,
(2) Electric field, electric potential, and charge density distributions in the particulate layer,
(3) Average electrical resistivity and positional dependence of resistivity,
(4) Electrical force holding the layer to the collection electrode,
(5) Prediction of the average electric field strength at the onset of electrical breakdown of the layer, based on a designated value of breakdown strength, and
(6) Prediction of what types of conditioning agents will be beneficial in reducing the resistivity of the particulate layer.

Background

In one commonly accepted picture of electrical breakdown of the dust layer, the gas trapped in the interstitial space breaks down electrically.[9–13] This breakdown results from the acceleration of free electrons to the gas ionization velocity which produces an avalanche condition similar to that at the corona electrode. Experimental measurements show that particulate layers may experience electrical breakdown at average electric field strengths across the layers of approximately 5–15 kV/cm.[15–17] For temperatures and pressures encountered in precipitators, it takes an electric field strength of approximately 15–30 kV/cm to cause electrical breakdown of the gas when the breakdown occurs over the thickness of the layer.[18] The field required for breakdown in a small cavity between particles may be much greater. This suggests that locally high electric fields must exist in the particulate layer to produce breakdown of the gas in the layer.

Any model that is proposed to describe the electrical characteristics of the dust layer must be capable of predicting the macroscopic behavior and any localized phenomena which will enhance electrical breakdown. The macroscopic electrical properties of the dust layer can be described by coupling the current transport equation and Poisson's Equation. The current transport equation is given in one dimension by

$$J = -D\frac{dC(x)}{dx} + bE(x)C(x) \tag{3}$$

where

J = charge carrier flux density ($\#/sec/m^2$),
D = diffusion coefficient of the charge carriers (m^2/sec),
C = concentration of the charge carriers ($\#/m^3$),
b = electrical mobility of the charge carriers ($m^2/V\text{-}sec$),
E = electric field intensity (V/m), and
x = position coordinate (m).

Poisson's Equation is given by

$$E'(x) = qC(x)/\epsilon \tag{4}$$

where

$E'(x) = \frac{dE}{dx}$ = the first derivation of the electric field,
q = charge on an individual charge carrier (C), and
ϵ = permittivity of the transport medium (C/V·m).

Two effects which will cause the local electric field to be larger than the average electric field are polarization in the dielectric layer and space charge in the layer. The local electric field due to polarization effects can be determined using standard techniques.[19,20] The effect on the local electric field due to space charge is obtained from the macroscopic description of the electrical properties.

Polarization Effect

The effect due to polarization can be estimated by treating the layer as a collection of spherical particles all of the same size and arranged in a cubic array. The problem is then to evaluate the effect of placing dielectric spheres in an applied electric field. For a parallel plate capacitor arrangement of metal electrodes containing a dielectric material, the polarization charge induced on the surface of the dielectric is neutralized by charge flowing in an external circuit. While this description is applicable to laboratory experiments on fly ash where parallel electrodes are used, it does not necessarily apply for fly ash layers on the collection plates of a precipitator. A dust layer in a precipitator has only one metal electrode with the other surface exposed to flue gas carrying a corona current. For high resistivity dust a surface charge[11,12] will be deposited on the layer by the corona current. The layer of surface charge will serve to impress a potential difference across the layer, and hence, the surface charge layer will act much like a second metal electrode. The mathematical description of the electrical properties of a dust layer in a precipitator will be quite similar to the laboratory case in which the layer is placed between two metal electrodes. The local electric field inside the volume of such a dielectric is computed by combining the contributions from all the dipoles of the particles with the applied electric field. Figure 1 shows the physical arrangement

and nomenclature that will be utilized in estimating the effect due to polarization.

When a dielectric sphere is placed in a uniform electric field the sphere becomes polarized. The induced electric field outside the sphere is that of a dipole with moment[19]

$$P = 4\pi\epsilon_0 a^3 \left(\frac{K-1}{K+2}\right) E \tag{5}$$

where

a = radius of the sphere (m),
ϵ_0 = permittivity of free space (C/V·m),
K = dielectric constant of the sphere, and
E = electric field effective in polarizing the dielectric sphere (V/m).

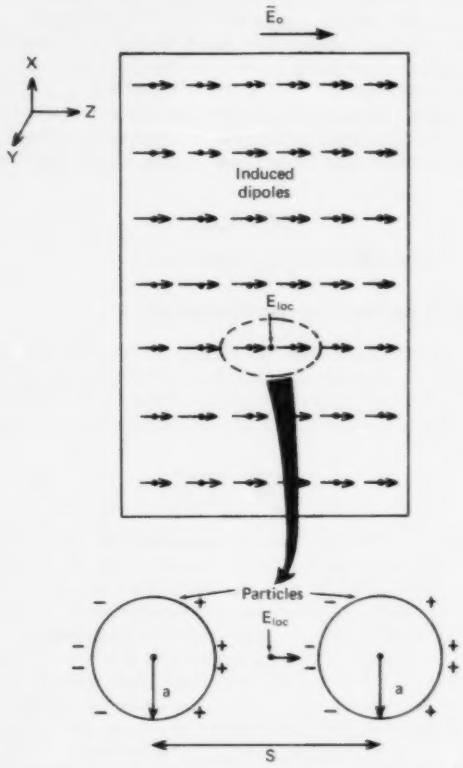

Figure 1. Physical arrangement and nomenclature for use in estimating the effect due to polarization.

When a dielectric sphere is located in a dielectric medium, the value of E is determined by the applied electric field and the electric field due to polarization of the dielectric medium. For molecules in a cubic lattice, Lorentz's method[20] for treating dipolar interactions gives the electric field at a molecular site as

$$E = \left(\frac{K+2}{3}\right) E_0 \tag{6}$$

where E_0 is the applied electric field. It is assumed that Eq. (6) can be applied to a cubic lattice of spherical, dielectric particles in order to obtain a reasonable estimate of the electric field effective in polarizing a particle.

Since E is the electric field effective in polarizing a particular sphere, it should be used to determine the dipole moment of the sphere. Thus, the dipole moment of a particular sphere is

$$P = 4\pi\epsilon_0 a^3 \left(\frac{K-1}{3}\right) E_0 \tag{7}$$

The local electric field at any point in the lattice is determined by superposing the electric field due to all the dipoles with the externally applied electric field. In order to calculate the local electric field, we look at a point centered between two dipoles on the cube axis parallel to the applied electric field. The electric field at this point is given by[19]

$$E_{loc} = E_0 + \frac{P}{4\pi\epsilon_0 S^3} \sum_{k=1}^{\infty} \sum_{i=-\infty}^{\infty} \sum_{j=-\infty}^{\infty} \times \frac{2[2(k-\frac{1}{2})^2 - i^2 - j^2]}{[i^2 + j^2 + (k-\frac{1}{2})^2]^{5/2}} \tag{8}$$

where S is the lattice spacing.

The triple summation in Eq. (8) accounts for the contributions from all the dipoles in the cubic array. The indices i, j, and k run along lattice sites in the x, y, and z directions, respectively. The factor of 2 arises due to symmetry and accounts for the pair of planes corresponding to a given value of k. Although the triple summation converges slowly, it can be evaluated numerically to yield a value of approximately 30. The local electric field is then given by

$$E_{loc} \approx E_0 [1 + 10(K-1)(a/S)^3] \tag{9}$$

If we assume that the particles are in contact with one another, then $S = 2a$ and

$$E_{loc} \approx E_0 [1 + 1.25(K-1)] \tag{10}$$

The local electric field strength can be several times larger than the applied (average) electric field strength, depending on the dielectric constant of the particles. The local electric field strength will be computed later for a range of dielectric constants which is typical of fly ash particles.

Space Charge Effect

The effect of space charge on the macroscopic electric field can be investigated by solving the problem involving the transport of charge carriers through the particulate layer. A simplified model is proposed in order to demonstrate that space charge effects can result in a significant enhancement of the electric field in the particulate layer. In this model, we assume that only one species carries the charge and that the gradient term in Eq. (3) can be neglected for all values of x. Figure 2 shows the nomenclature used in the development of the model.

Suppose a potential difference is applied across a layer of thickness L. Eq. (3) and (4) can be solved simultaneously using the assumptions described above. The electric field can be related to the charge carrier flux density through

$$E(x) = E(0) \left[1 + \frac{2qJx}{\epsilon b E^2(0)}\right]^{1/2} \tag{11}$$

where $E(0)$ is the electric field intensity at one of the boundaries. It should be kept in mind that ϵ is the permittivity of the particles, and b is the mobility of ions in the particles. The mobility of ions in the semi-insulating particles is expected to be much smaller than the ionic mobility of flue gas.

After integrating Eq. (11), one can show that the potential difference across the layer is given by

$$V(L) - V(0) = \frac{2}{3} \frac{\epsilon b E^3(0)}{2qJ} \left[1 - \left(1 + \frac{2qJL}{\epsilon b E^2(0)}\right)^{3/2}\right] \tag{12}$$

where $V(0)$ is the potential at the same boundary at which $E(0)$ is evaluated. If the last term in equation (12) dominates, it follows that

$$\frac{V(L) - V(0)}{L} \approx -\frac{2}{3} E(L) \tag{13}$$

Note that the left hand side of Eq. (13) is just the average electric field (E_{ave}) in the layer, while $E(L)$ represents the maximum value of the electric field in the layer. Thus, in this

simplified model, the maximum electric field can be 1.5 times larger than the average electric field.

Combined Effect of Polarization and Space Charge

One can relate the maximum local electric field strength in the layer (E_{loc}) to the average electric field strength by combining the effects due to polarization and space charge. With space charge present, the maximum electric field strength effective in polarizing particles is $(K + 2)E(L)/3$, and this value should be used in Eq. (5) for purposes of determining electrical breakdown criteria. Thus, the maximum local electric field strength in the layer is given by

$$E_{loc} \approx E(L)\,[1 + 1.25\,(K - 1)] \approx 1.5\,[1 + 1.25\,(K - 1)]\,E_{ave} \quad (14)$$

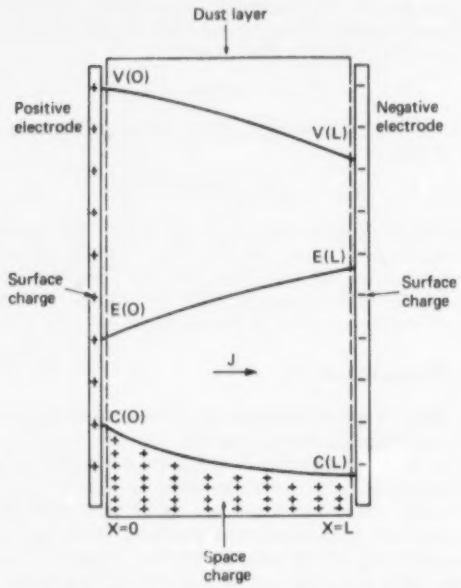

Figure 2. Nomenclature used in the description of the macroscopic electrical properties of a precipitated dust layer.

This relationship depends on the dielectric constant of the layer or, more specifically, of the individual particles. Since, in the case of fly ash particles, the dielectric constant may vary over a certain range from one source to another, it is desirable to compute the maximum electric field strength as a function of dielectric constant. The average value of the electric field for which breakdown will occur can also be computed as a function of dielectric constant by specifying a breakdown strength (E_B) for the trapped gas. For illustrative purposes, the breakdown strength of the gas will be assumed to be that of air. Paschen's Law[11,21,22] is used to estimate the breakdown strength of air in the gas pockets of the layer. It is assumed that the breakdown strength of air varies with absolute temperature as (293°K/T). Table I shows the results of calculations for several cases of interest. Notice that the description of dielectric breakdown obtained from the simplified model presented here is consistent with the observation that breakdown in fly ash layers often occurs for average fields in the range 5–15 kV/cm.

If the dielectric constant and the average resistivity of a particular fly ash are measured in the appropriate environment, then a practical upper bound on the operating current density can be established to avoid dielectric breakdown. If the dielectric constant is known, we can compute the average electric field required for breakdown from Eq. (14). The current density corresponding to this average electric field would constitute the upper bound on the operating current. The condition which must be satisfied in order to avoid breakdown is

$$q_s J < E_{ave}/\rho \quad (15)$$

where E_{ave} is computed for breakdown.

Extending the Macroscopic Description

The use of more realistic models to describe the charge transport in the dust layer is expected to yield a much higher space charge effect than predicted by the simplified model discussed earlier. If there are any regions in the layer in which

$$\left|\frac{dC}{dx}\right| \sim \left|\frac{bEC}{D}\right| \quad (16)$$

the electric field computed by neglecting the charge carrier density gradient may not provide an adequate representation. This is especially true near the boundaries where the charge carrier gradients are likely to give their greatest contribution to the current. If the charge carrier density gradient is large near a boundary and has a sign which tends to oppose the current produced by the electric field, then the electric field must increase faster in this region than would be predicted by the simplified model. Under these conditions, the electric field may be considerably larger near the boundary than Eq. (11) would predict. This rapid increase in the electric field may not be reflected very strongly in the average electric field because it occurs over such a small region of the layer.

Table I. Average electric field at breakdown for various dielectric constants, temperatures, pressures, and cavity sizes.

		Pressure 760mm Hg Cavity size 10μ			Pressure 760mm Hg Cavity size 100μ		
		[a]E_B = 375 kV/cm T = 293°K	E_B = 260 kV/cm T = 422°K	E_B = 175 kV/cm T = 616°K	E_B = 92 kV/cm T = 293°K	E_B = 64 kV/cm T = 422°K	E_B = 44 kV/cm T = 616°K
K	E_{loc}/E_{ave}	E_{ave} for Breakdown (kV/cm)	E_{ave} for Breakdown (kV/cm)	E_{ave} for Breakdown (kV/cm)	E_{ave} for Breakdown (kV/cm)	E_{ave} for Breakdown (kV/cm)	E_{ave} for Breakdown (kV/cm)
3	5.25	71.4	49.5	33.9	17.5	12.2	8.38
4	7.13	52.6	36.5	25.0	12.9	8.98	6.17
5	9.20	40.8	28.3	19.3	10.0	6.96	4.78
6	10.9	34.5	23.9	16.4	8.46	5.88	4.04
7	12.8	29.4	20.4	14.0	7.22	5.02	3.45
8	14.6	25.6	17.8	12.2	6.29	4.37	3.01
9	16.5	22.7	15.8	10.8	5.58	3.88	2.67
10	18.4	20.4	14.1	9.68	5.01	3.48	2.39
11	20.3	18.4	12.8	8.79	4.54	3.16	2.17
12	22.1	16.9	11.7	8.04	4.16	2.89	1.99

[a] Breakdown strength based on Paschen's law.

As another consideration in a more realistic model, the dust layer must be considered to be between two blocking electrodes so that there must be at least two mobile charge carrier species of opposite sign. This would be the case for a laboratory experiment using parallel electrodes. A fly ash layer in a precipitator has only one real electrode. However, since the ions deposited on the surface of the layer by the corona current do not move directly through the fly ash, they act much like a metal electrode. Since this virtual electrode does not supply ionic charge carriers to the layer, it will behave much like a blocking metal electrode.

In order to obtain solutions to the transport equations, the mobilities and diffusion coefficients for the two charge carrier species must be known. If the Nernst-Einstein relationship can be applied, then the mobility and diffusion coefficient for a given species are related linearly and a good value of either one of these parameters can be used to determine a good value of the other. The current density due to each charge carrier species and the voltage applied across the layer must be specified. The boundary conditions available are the concentrations of both species at both boundaries and the electric field intensity at both boundaries. Any combination of 3 of these 6 boundary conditions is sufficient to determine a unique solution for the two species case.

At the present time, experimental data, which are necessary for constructing appropriate models and for use in comparing the predictions of models, are not very complete or are not available. Certain experimental studies need to be performed to determine appropriate values of the parameters and boundary conditions that must be utilized in modeling the electrical phenomena. These studies include the following:

(1) Experiments on different dusts to determine whether electrical breakdown of the layer is due to gas breakdown or to particle breakdown;

(2) Measurements on different dusts in simulated flue gas environments to determine the electric potential distribution in the layer and the concentration profiles of the charge carrying species for different voltages across the layer;

(3) Measurements on different dusts in simulated flue gas environments to determine transference numbers, activation energies, conductivities, diffusion coefficients, and mobilities of the different charge carrying species; and

(4) Measurements of the dielectric constant of different dusts in simulated flue gas environments.

Summary and Conclusions

A model which combines the effects of polarization and space charge appears to offer the potential of describing the electrical characteristics of dust layers deposited in the electrostatic precipitation process. This type of model predicts electrical breakdown of a dust layer at an average electric field strength across the layer which is consistent with experimental data.[15-16] In addition, the macroscopic electrical properties of the dust layer are obtained. The validation and further development of this type of model depend on the acquisition of certain data which are needed for use in specifying parameters and boundary conditions characteristic of dust layers. Although electrical breakdown of the dust layer has been attributed to breakdown of the gas trapped in the interstitial space, the model is equally applicable to the case where the breakdown is due to the particles in the dust layer breaking down electrically instead of the gas.

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